Looking for ALPs at PSI

Axion-like-particles search with the nEDM spectrometer

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LTP Seminar 25 November 2019 PSI

Strong CP problem & axions

- Baryon asymmetry → CP violation (CPV)
- θ-term in $\mathcal{L}_{\mathrm{QCD}} < 10^{-9} \sim 10^{-10}$ → strong CP problem

- Peccei-Quinn theory: SM has an additional global U(1) chiral symmetry → $\mathrm{U(1)_{PQ}}$

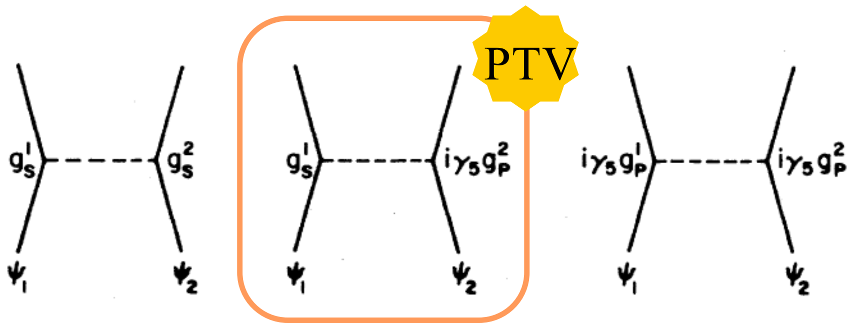
θ	⇒	$a(x) / f_a$
Static CP Viol. Angle		Dynamical CP conserving Axion field

Ref.: R.D. Peccei, Invisibles 2015 workshop, Madrid June 2015, "The Strong CP Problem and Axions".

→ spontaneously broken $\mathrm{U(1)_{PQ}}$ → new pseudo-scalar boson: axion

Ref.: R.D. Peccei and H. R. Quinn, PRL 38, (1977) 1440-1443.

- Moody / Wilczek: macroscopic forces mediated by very light, weakly coupled bosons



Coupling to fundamental fermions:
scalar (g_s) & pseudo-scalar (g_p) vertices

Ref.: J. E. Moody and F. Wilczek, PRD 30 (1984), 130-138.

Fifth force and ALPs

- PT-violating, spin-dependent "fifth force"
  - A polarized & an unpolarized particle

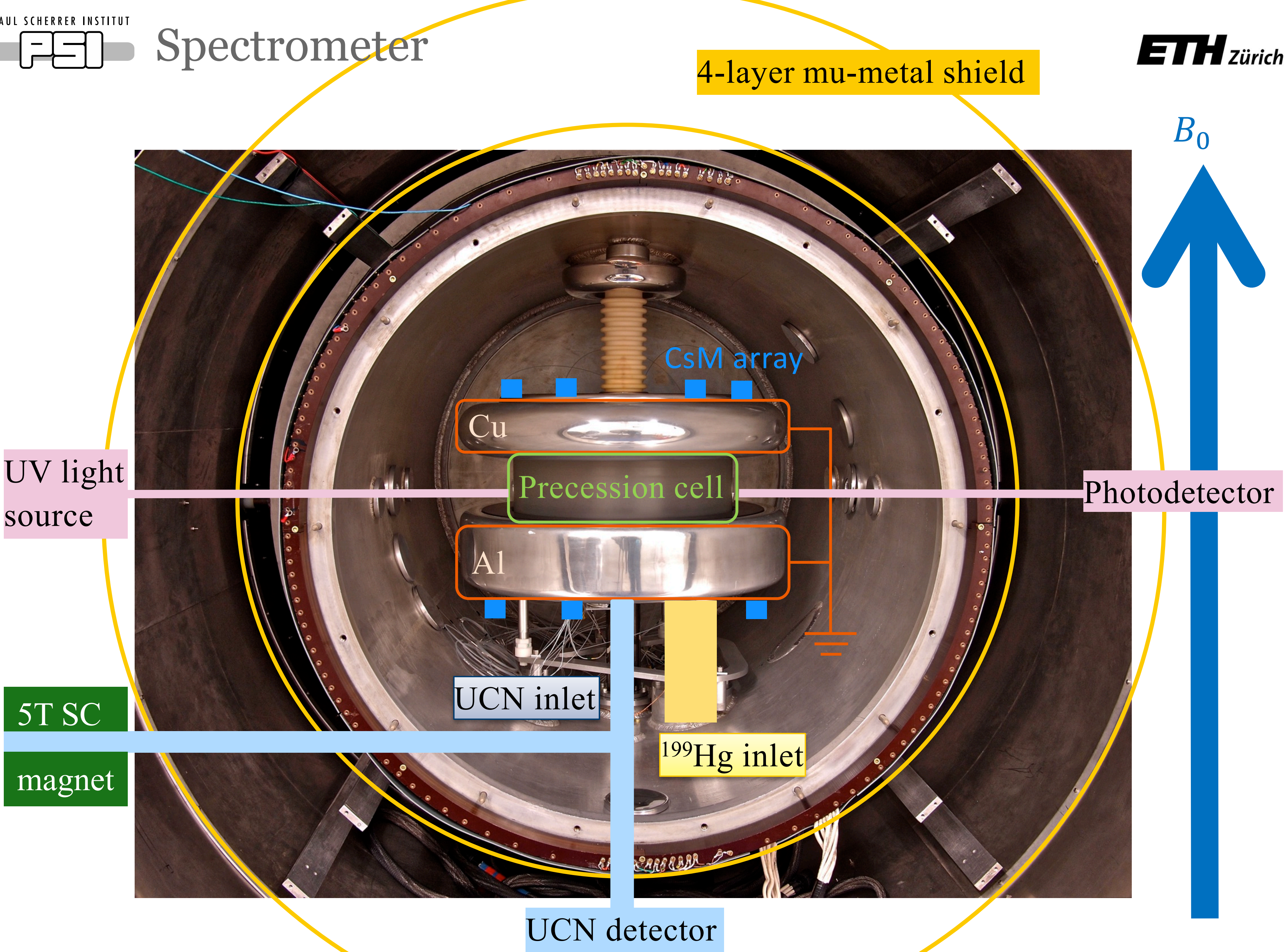
- Axion: $g_s g_p \sim \theta \frac{m_q{}^2}{f_a{}^2} \sim \theta m_a{}^2$
  - EDM bounds: $\theta \lesssim 10^{-10}$
  - Peccei-Quinn scale: $f_a \sim 10^9 - 10^{12}$ GeV

Ref.: S. Mantry, M. Pitschmann and M. J. Ramsey-Musolf, PRD 90, 054016 (2014).

- Axion-like particles (ALPs)
  - unrelated to θ-term → not constrained by EDM limits
  - BSM theories
  - DM candidates

Lab-scale "fifth force" observation with the nEDM spectrometer @ PSI

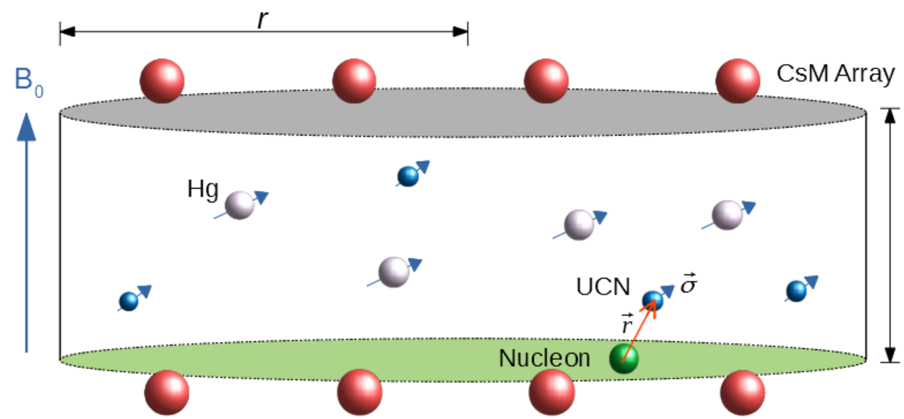
Spectrometer



Search for ALPs

- Search for "the fifth force" (short-range spin-dependent interaction)

g_s / g_p: scalar / pseudoscalar coupling constant
ϕ : unpolarized particle
ψ : polarized particle



- Spin-dependent potential: $V(\boldsymbol{r}) = g_\mathrm{s} g_\mathrm{p} \frac{(\hbar c)^2}{8\pi m c^2} (\hat{\boldsymbol{\sigma}} \cdot \hat{\boldsymbol{r}}) (\frac{1}{r\lambda} + \frac{1}{r^2}) \mathrm{e}^{-r/\lambda}$

- Pseudo-magnetic field: $b(z) = g_\mathrm{s} g_\mathrm{p} \frac{\hbar \lambda N}{2\gamma m} (1 - \mathrm{e}^{-d/\lambda})(\mathrm{e}^{-z/\lambda})$ $\quad N$: nucleon density

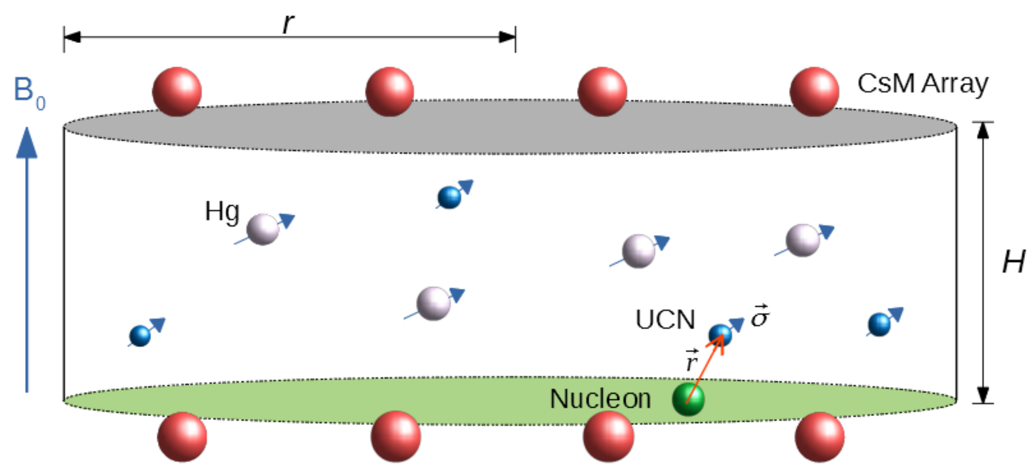
$$b_\mathrm{UCN} = \int_{-H/2}^{H/2} g_\mathrm{s} g_\mathrm{p} \frac{\hbar \lambda}{2\gamma m} (1 - \mathrm{e}^{-d/\lambda}) \left[N_\mathrm{bottom} \mathrm{e}^{-\frac{z+H/2}{\lambda}} - N_\mathrm{top} \mathrm{e}^{-\frac{-z+H/2}{\lambda}} \right] \rho_\mathrm{UCN}(z)\, \mathrm{d}z$$

$\rho_\mathrm{UCN}(z) = \frac{1}{H}(1 + \frac{12\langle z \rangle}{H^2} z)$, $\langle z \rangle$: center-of-mass offset, (-2)~(-4) mm

Observable: $R = \frac{f_n}{f_{Hg}}$

- $R^{\uparrow\downarrow} = \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}\left(1 \pm \frac{b_{UCN}}{B_0}\right) \longrightarrow b_{UCN} = \frac{R^{\uparrow} - R^{\downarrow}}{R^{\uparrow} + R^{\downarrow}} B_0 \longrightarrow g_s g_p$

- Systematic effects: $R = \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}(1 + \delta_{Grav} + \delta_{Trans} + \delta_{Earth})$
  - δ_{Grav}: gravitational shift ($\delta_{Grav} = \pm\frac{\langle z\rangle}{B_0} G_z = \pm\frac{\langle z\rangle}{B_0}\frac{dB_z}{dz}$, $\langle z\rangle < 0$)
  - δ_{Trans}: transverse shift ($\delta_{Trans} = \frac{\langle {B_T}^2\rangle}{2{B_0}^2}$)
  - δ_{Earth}: Earth's rotational shift ($\delta_{Earth} = \mp 1.4 \times 10^{-6}$)



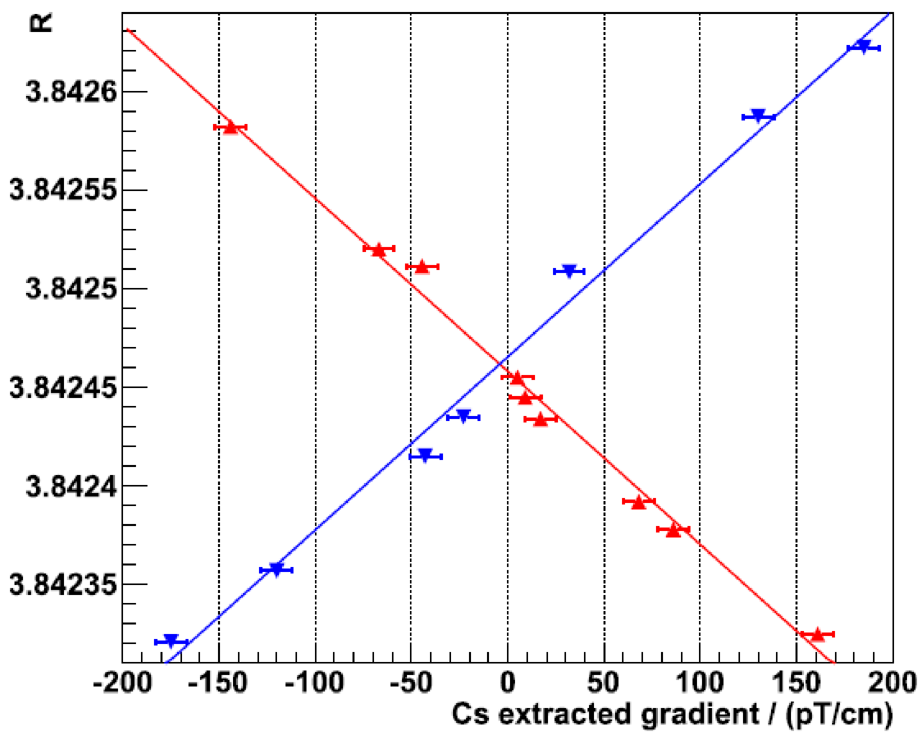
Ref.: S. Afach et al., PLB 739 (2014) 128-132.

Crossing-point analysis

- Observe R value under different gradients $G_z = \frac{\mathrm{d}B_z}{\mathrm{d}z}$

$$R^{\uparrow\downarrow} = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}(1 + \delta_\mathrm{Grav} + \delta_\mathrm{Trans} + \delta_\mathrm{Earth})$$

gravitational shift: $\delta_\mathrm{Grav} = \pm\frac{\langle z\rangle}{B_0}G_z = \pm\frac{\langle z\rangle}{B_0}\frac{\mathrm{d}B_z}{\mathrm{d}z}$, $\langle z\rangle < 0$



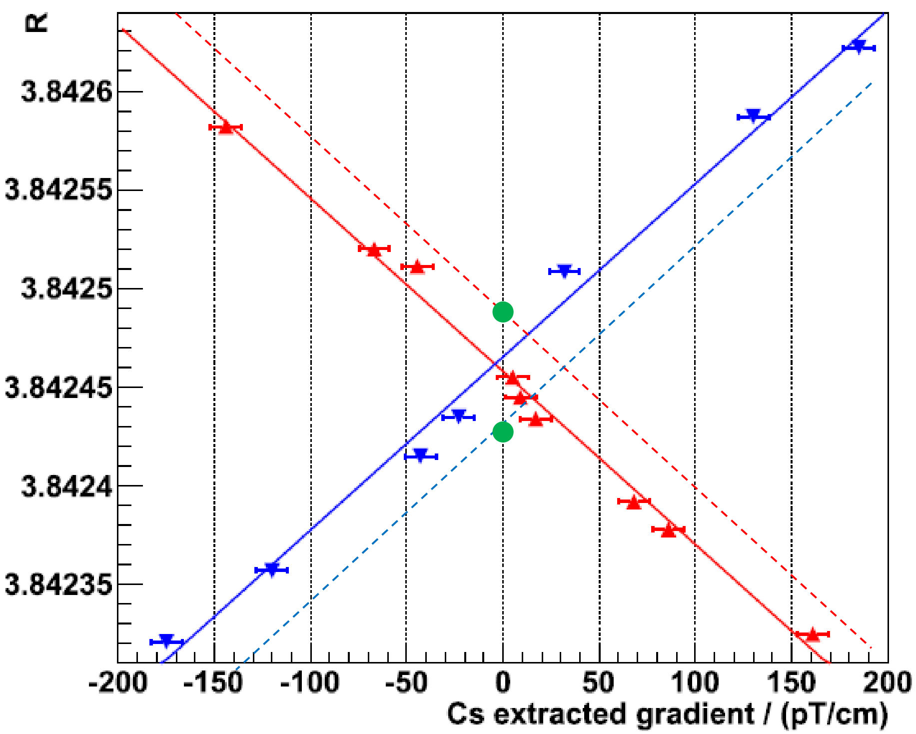
Ref.: S. Afach et al., PLB 739 (2014) 128-132.

Crossing-point analysis

- Observe R value under different gradients $G_z = \frac{\mathrm{d}B_z}{\mathrm{d}z}$

$$R^{\uparrow\downarrow} = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\left(1 + \delta_\mathrm{Grav} + \delta_\mathrm{Trans} + \delta_\mathrm{Earth} \pm \frac{b_\mathrm{UCN}}{B_0}\right)$$

gravitational shift: $\delta_\mathrm{Grav} = \pm\frac{\langle z\rangle}{B_0}G_z = \pm\frac{\langle z\rangle}{B_0}\frac{\mathrm{d}B_z}{\mathrm{d}z}$, $\langle z\rangle < 0$

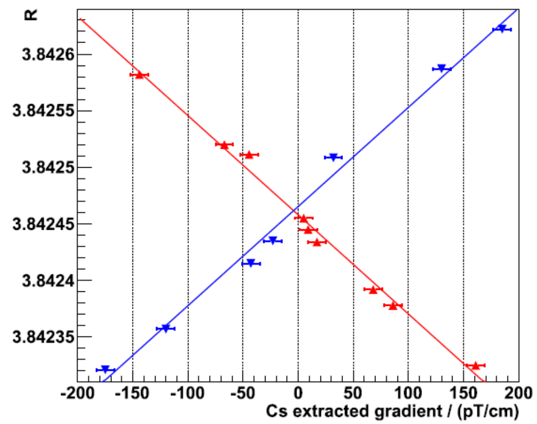


$$b_\mathrm{UCN} = \frac{R^{\uparrow} - R^{\downarrow}}{R^{\uparrow} + R^{\downarrow}} B_0$$

Ref.: S. Afach et al., PLB 739 (2014) 128-132.

Approaches for sensitivity improvement

- In 2015, our collaboration published a result of the limit on $g_s g_p$ coupling.
  To improve the sensitivity in measurements, two approaches were taken:



Refs.: S. Afach et al., PLB 739 (2014) 128-132.
S. Afach et al., PLB 745 (2015) 58-63.

1. Replacement of the top electrode:

Al → Cu

data taken in 2017

2. Analyze magnetic-field gradient:

online CsM data + offline field maps

analysis in progress

1. Replacement of the top electrode

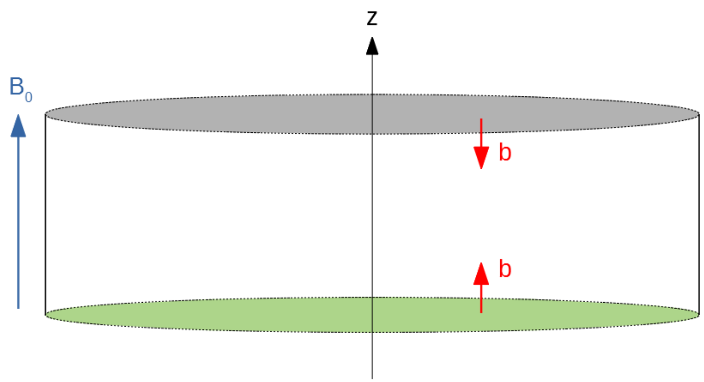
$$b_{\mathrm{alps}}(z) = g_s g_p \frac{\hbar\lambda}{2\gamma m}\left(1-\mathrm{e}^{-d/\lambda}\right)\left[N_{\mathrm{bottom}}\mathrm{e}^{-\frac{z+H/2}{\lambda}} - N_{\mathrm{top}}\mathrm{e}^{-\frac{-z+H/2}{\lambda}}\right]$$

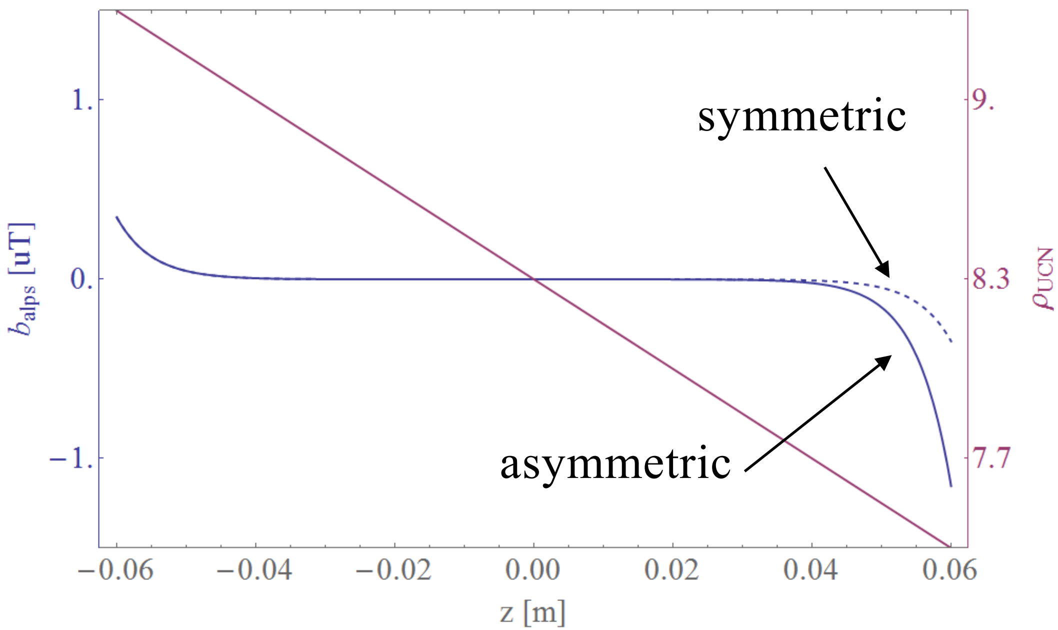
N: nucleon density

- Original: Al-Al electrodes (symmetric)
  – only sensitive to UCN density distribution

- New: Cu-Al electrodes (asymmetric)
  – Larger (3×) nucleon density for Cu
  – asymmetric pseudo-magnetic field

N.B. Not to scale!
b_{alps} only sensitive at close distances.





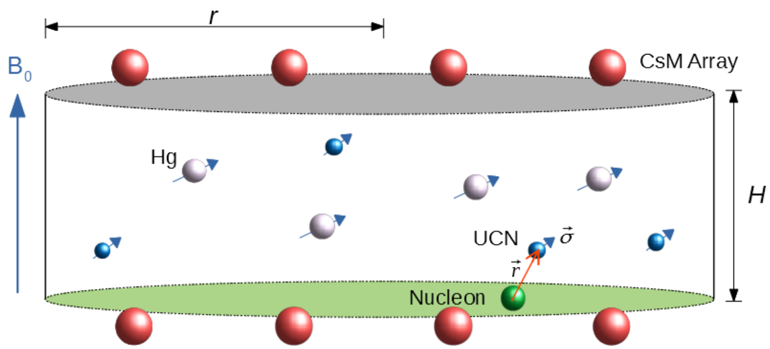
Polynomial expansion

- Polynomial expansion of the magnetic field components:

$$\boldsymbol{B}(\boldsymbol{r}) = \sum_l \sum_{m=-(l+1)}^{+(l+1)} G_{l,m} \begin{pmatrix} \pi_{x,l,m}(\boldsymbol{r}) \\ \pi_{y,l,m}(\boldsymbol{r}) \\ \pi_{z,l,m}(\boldsymbol{r}) \end{pmatrix}$$

$\boldsymbol{\pi}_{l,m}$ are harmonic polynomials in x, y, z of degree l, order m.

- Fit measured scalar CsM values to



$$B_z(\boldsymbol{r}) = \sum_l \sum_{m=-l}^{+l} G_{l,m}\, \pi_{z,l,m}(\boldsymbol{r}) = G_{0,0} + G_{1,-1}\, y + G_{1,0}\, z + G_{1,1}\, x + \cdots$$

Ref.: C. Abel et al., PRA 99, 042112 (2019).

Error on magnetic-field gradient G_z

- In 2015, we performed 2nd–degree fit with 11 CsM:

Ref.: S. Afach et al., PLB 739 (2014) 128-132.

$$B_z(\boldsymbol{r}) = \sum_{l} \sum_{m=-l}^{+l} G_{l,m}\, \pi_{z,l,m}(\boldsymbol{r}) = G_{0,0} + G_{1,-1}\, y + G_{1,0}\, z + G_{1,1}\, x + \cdots$$

up to $l = 2$: $G_{0,0}, G_{1,-1}, G_{1,0}, G_{1,1}, G_{2,-2}, G_{2,-1}, G_{2,0}, G_{2,1}, G_{2,2}$

Error on $G_{1,0}$ ($\sigma_{G_{1,0}}$) was calculated with "Jackknife" procedure:

$G_{1,0}$ (10 CsM) | G (10 (| G (10 (| $G_{1,0}$ (10 CsM) …

× 11 times → $\sigma_{G_{1,0}}$: 8 pT/cm

- In 2017, we had 14-15 CsM → fit up to 2nd–degree

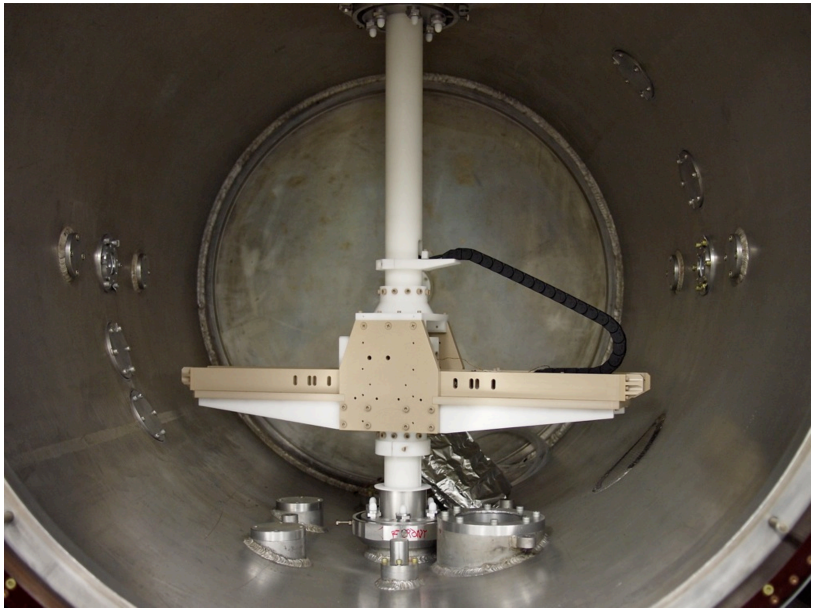
higher-degree coefficients

2. Analyze magnetic-field gradient G_z

online CsM data + offline field maps

During the experiment, used 14-15 optically-pumped ^{133}Cs magnetometers.

"Mapping campaign"



- Field maps: sensitive in 3 coordinates (r, φ, z)
- CsM: sensitive in 1 coordinate (z)

Error on magnetic-field gradient G_z

- Remove higher-degree fields, and perform 2nd–degree fit with 14-15 CsM:

Sol. → online CsM data + offline field maps

$$\pm\left|\overrightarrow{B_{\mathrm{CsM}}}\right| \quad - \sum_{l=3}^{6}\left[G_{l,m}\,\pi_z\right] \longrightarrow \sum_{l=0}^{2}\left[G_{l,m}\,\pi_z\right]$$

$$B_z(\boldsymbol{r}) = \sum_{l}\sum_{m=-l}^{+l} G_{l,m}\,\pi_{z,l,m}(\boldsymbol{r}) = G_{0,0} + G_{1,-1}\,y + \boxed{G_{1,0}}\,z + G_{1,1}\,x + \cdots$$

up to $l = 2$: $G_{0,0}, G_{1,-1}, G_{1,0}, G_{1,1}, G_{2,-2}, G_{2,-1}, G_{2,0}, G_{2,1}, G_{2,2}$

$\sigma_{G_{1,0}}$: 1 pT/cm

Crossing-point analysis --- preliminary

- Observe R value under different gradients $G_z = \frac{dB_z}{dz}$

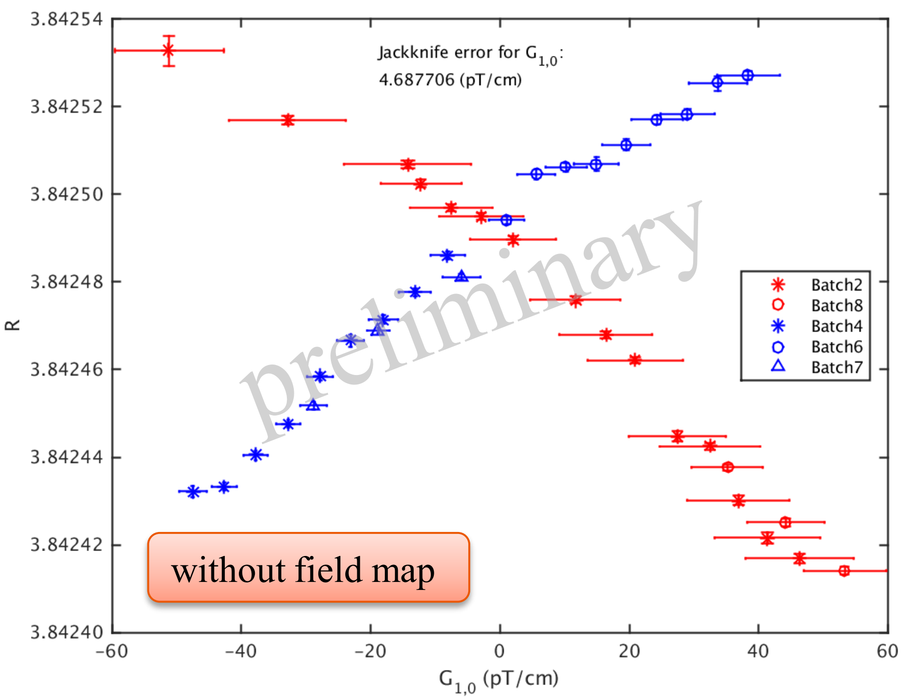
$$R^{\uparrow\downarrow} = \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}(1 + \delta_{Grav} + \delta_{Trans} + \delta_{Earth})$$

gravitational shift: $\delta_{Grav} = \pm\frac{\langle z\rangle}{B_0}G_z = \pm\frac{\langle z\rangle}{B_0}\frac{dB_z}{dz}$, $\langle z\rangle < 0$

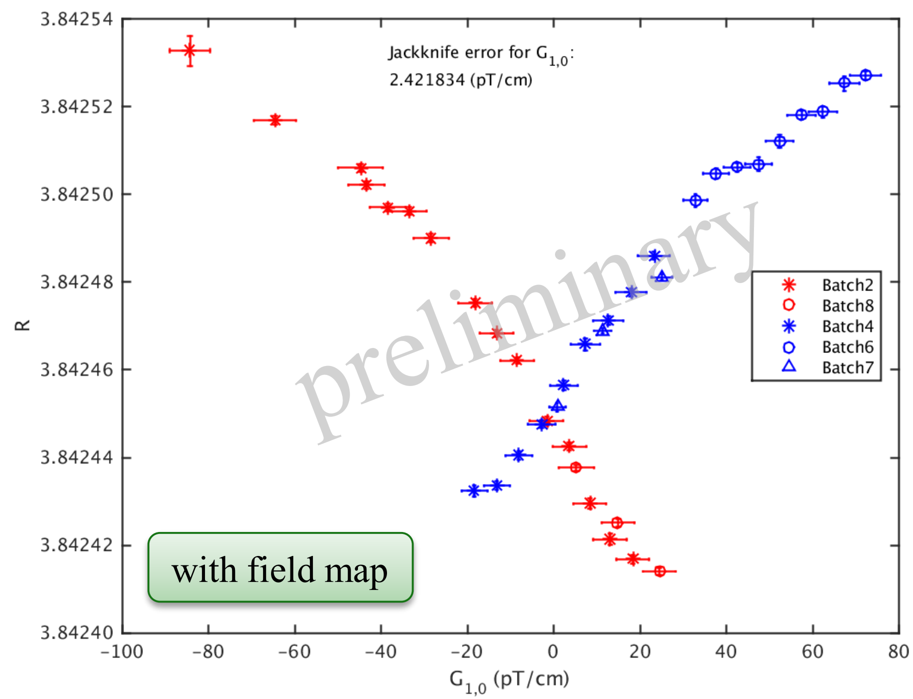
$\pm\left|\overrightarrow{B_{CsM}}\right| - \sum_{l=3}^{6}[G_{l,m}\,\pi_z]$

fit with $\sum_{l=0}^{2}[G_{l,m}\,\pi_z]$

Corrected for δ_{Earth}



without field map



with field map

Estimated sensitivity gain in $g_s g_p$

- $R^{\uparrow\downarrow} = \frac{f_n}{f_{Hg}} = \frac{\gamma_n}{\gamma_{Hg}}(1 \pm \frac{b_{UCN}}{B_0}) \longrightarrow b_{UCN} = \frac{R^{\uparrow}-R^{\downarrow}}{R^{\uparrow}+R^{\downarrow}} B_0 \longrightarrow g_s g_p$
- $R = \frac{\gamma_n}{\gamma_{Hg}}(1 + \delta_{Grav} + \delta_{Trans} + \delta_{Earth})$
  - $\delta_{Grav} = \pm \frac{\langle z \rangle}{B_0} G_z$: G_z error 8 pT/cm → 1 pT/cm
  - $\delta_{Trans} = \frac{\langle {B_T}^2 \rangle}{2{B_0}^2}$: $\langle {B_T}^2 \rangle$ error 0.5 nT^2(↑) / 0.7 nT^2(↓) → 0.3 nT^2

Ref.: N. Ayres' PhD thesis (2018).

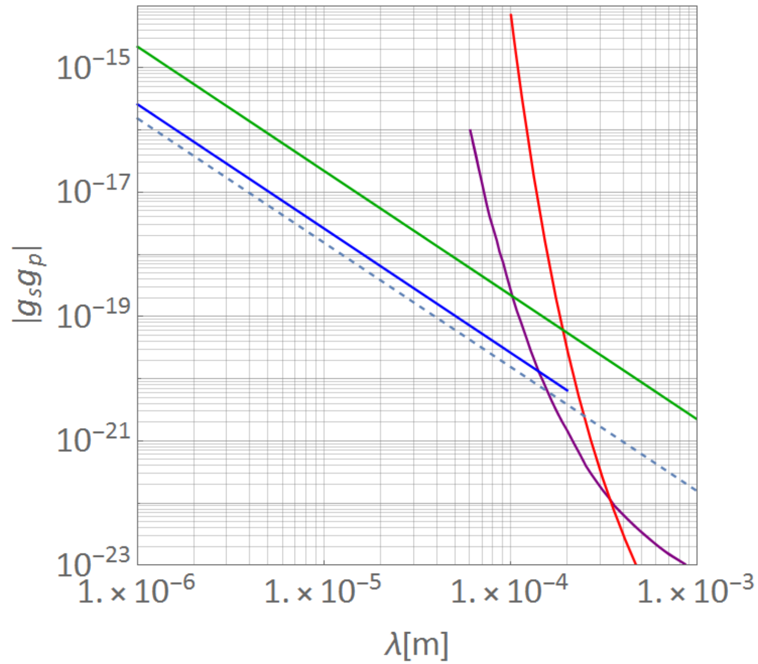
— ^{129}Xe / ^{131}Xe clock comparison, NG Corp.(2013)

— ^{3}He / ^{129}Xe clock comparison, Berlin(2013)

— UCN / ^{199}Hg clock comparison, PSI(2015)

— ^{3}He depolarization, ILL(2015)

- - - Anticipated UCN / ^{199}Hg clock comparison from PSI 2017 data



Summary and outlook

- ALPs serve as candidates for cold dark matter and BSM searches
- Explained the measurement method
- Introduced two approaches to improve the sensitivity

Final goal:

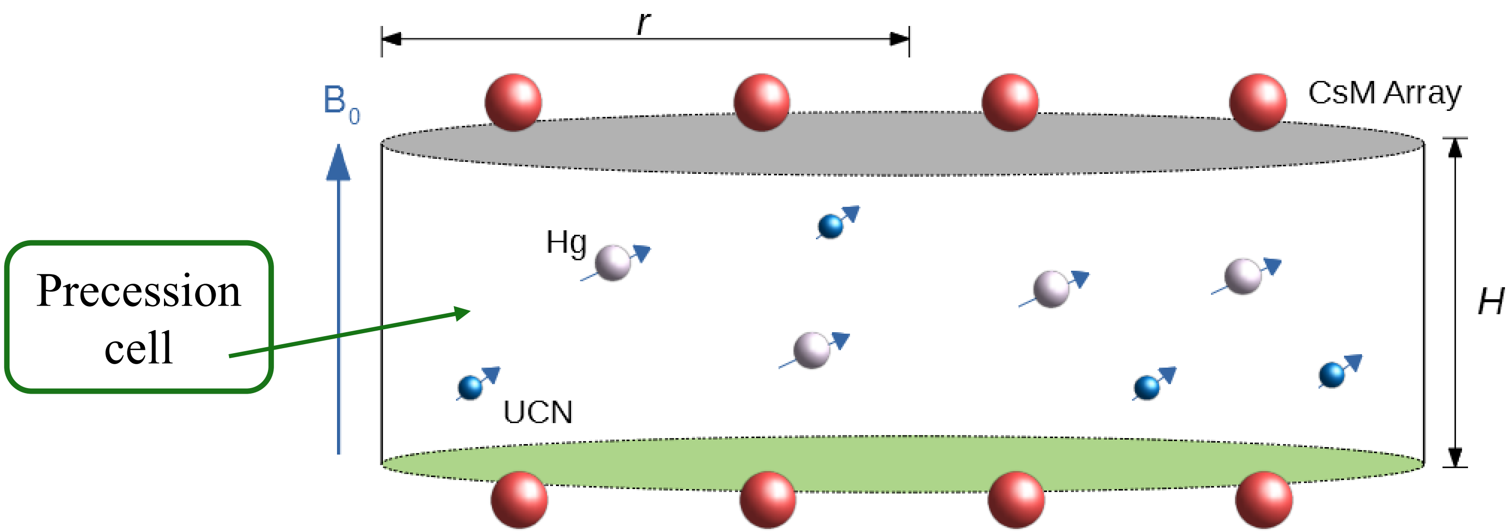
Achieve a new upper limit on couplings of the five-forth mediated by ALPs

or

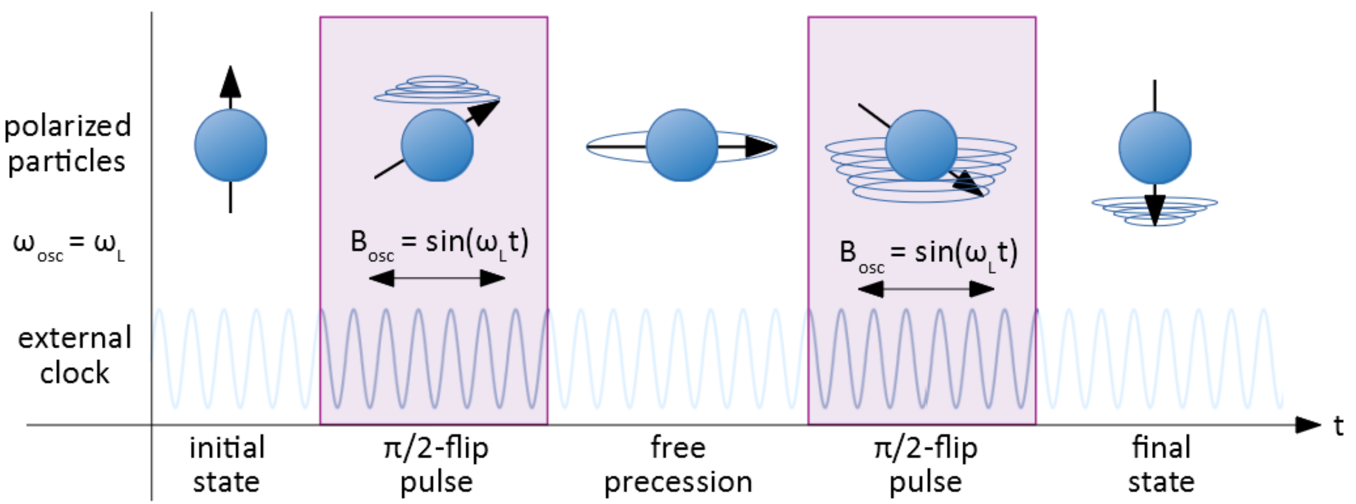
find ALPs

Thank you for your attention!

Ramsey's method of oscillating field



$B_0 = 1\ \mu T$
$H = 12$ cm
$r = 23.5\ cm$

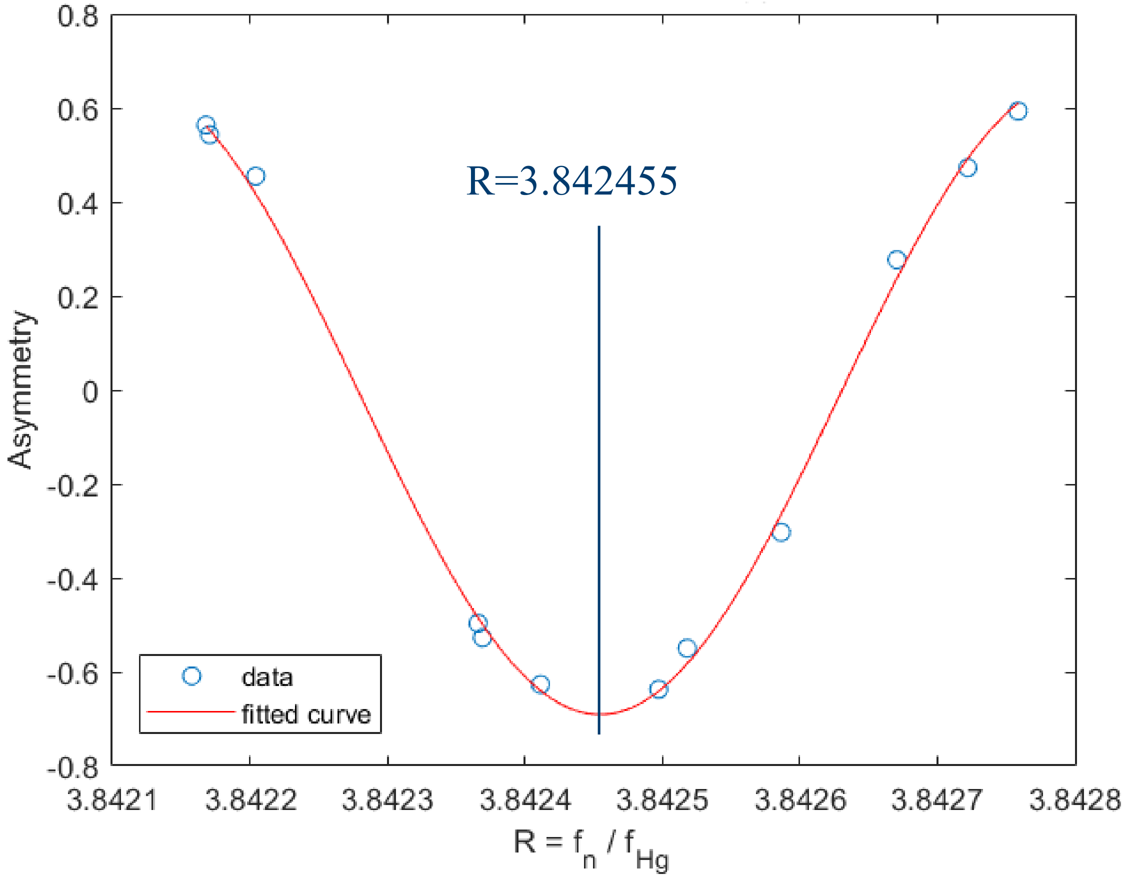


Ref.: N. F. Ramsey, Phys. Rev. 78 (1950), 695-699.

Ramsey's fringe

- Asymmetry: $A = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} \approx A_{off} - \alpha \cos\left[2\pi \left(\frac{f_n}{f_{Hg}} - R\right) T' \langle f_{Hg} \rangle\right]$

fit equation and extract R for each run



A_{off}: offset

α: visibility

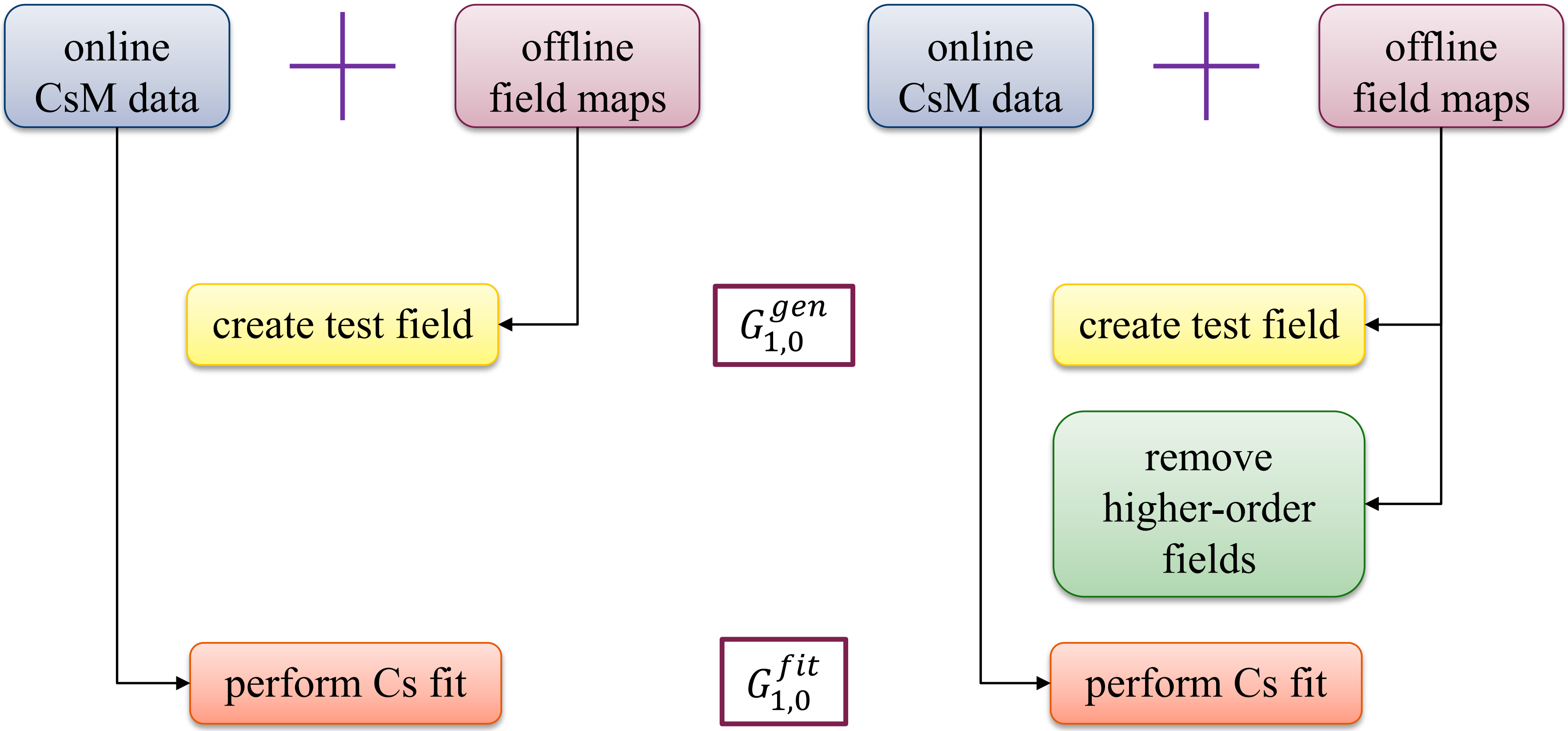
T': total time $= T + \frac{4\tau}{\pi}$

T: free precession time

τ: π − pulse time

Analysis method (1)

- Normal 2^{nd}-order fit
- New analysis method



$$\Delta G_{1,0} \equiv G_{1,0}^{fit} - G_{1,0}^{gen}$$

Analysis method (2)

- Procedure:

1. Create 200 random sets of test fields from field-map gradients, ∀ 14 CsM

$$\overrightarrow{B_{test}}(\boldsymbol{r}) = \sum_{l=0}^{6} \sum_{m=-(l+1)}^{+(l+1)} \left[\left(G_{l,m} + \delta_{G_{l,m}} \right) \vec{\pi}(\boldsymbol{r}) \right] \rightarrow G_{1,0}^{gen} = G_{1,0} + \delta_{G_{1,0}}$$

Gaussian distributed error with $\sigma_{G_{l,m}}$ from field map

$$\boldsymbol{B}(\boldsymbol{r}) = \sum_{l,m} G_{l,m} \begin{pmatrix} \pi_{x,l,m}(\boldsymbol{r}) \\ \pi_{y,l,m}(\boldsymbol{r}) \\ \pi_{z,l,m}(\boldsymbol{r}) \end{pmatrix}$$

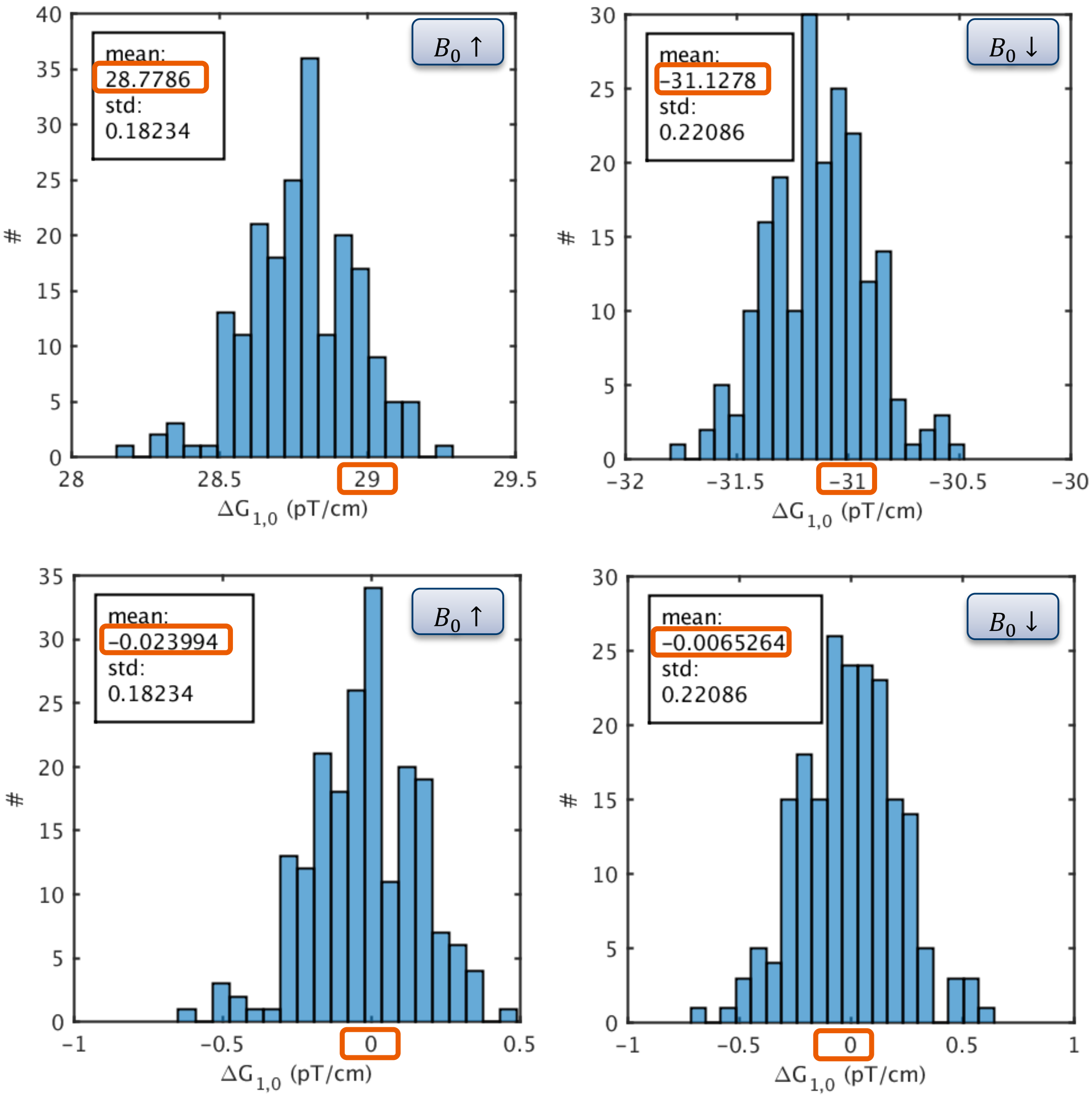
#:l	m	gradient	error
#=unitless	unitless	pT/cm^l	pT/cm^l
%:int	int	double	double
0	-1	-849.177399644	370.996357099
0	0	-1037790.32376	129.049189258
0	1	318.72907668	215.84379047
1	-2	-28.0309578842	2.75721881931
1	-1	-9.31203613085	7.02936080038
1	0	12.9352612637	10.986420738 ($\sigma_{G_{l,m}}$)
1	1	15.181805632	21.3449890229
1	2	-8.89865826303	3.0954716399

… up to $l = 6$

2. Perform Cs fit on $\pm\left|\overrightarrow{B_{test}}\right| \rightarrow G_{1,0}^{fit}$

3. Compare $G_{1,0}^{fit}$ to $G_{1,0}^{gen}$: $\Delta G_{1,0} \equiv G_{1,0}^{fit} - G_{1,0}^{gen}$

Simulated results (1)



Normal 2nd-order fit :

$$\pm\left|\overrightarrow{B_{test}}\right|$$

$$\longrightarrow \sum_{l=0}^{2}\left[G_{l,m}\,\pi_z\right] \rightarrow G_{1,0}^{fit}$$

$$\Delta G_{1,0} \equiv G_{1,0}^{fit} - G_{1,0}^{gen} \sim 30 \text{ pT/cm}$$

With higher-order removal:

$$\pm\left|\overrightarrow{B_{test}}\right| - \sum_{l=3}^{6}\left[G_{l,m}\,\pi_z\right]$$

$$\longrightarrow \sum_{l=0}^{2}\left[G_{l,m}\,\pi_z\right] \rightarrow G_{1,0}^{fit}$$

$$\Delta G_{1,0} \equiv G_{1,0}^{fit} - G_{1,0}^{gen} < 0.1 \text{ pT/cm}$$

CsM offsets

Ref.: S. Afach et al., PLB 739 (2014) 128-132.

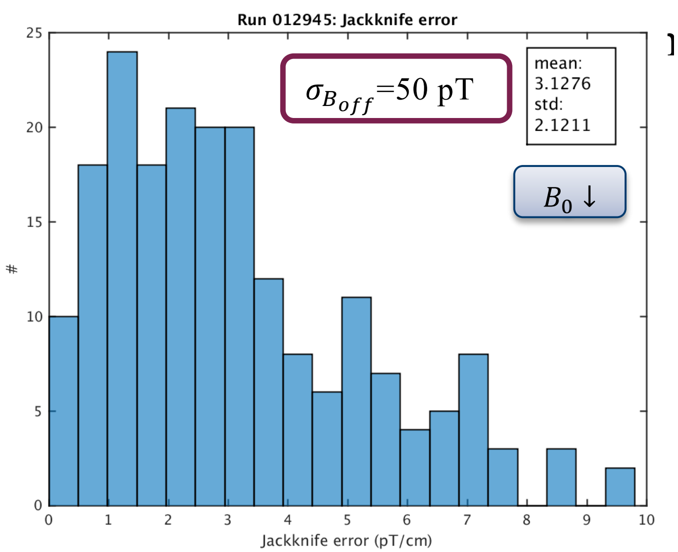
- Jackknife procedure: used 11 CsM (4 top + 7 bottom):
  11 measurements, performed 2nd-order fit with 10 CsM → σ = 8 pT/cm

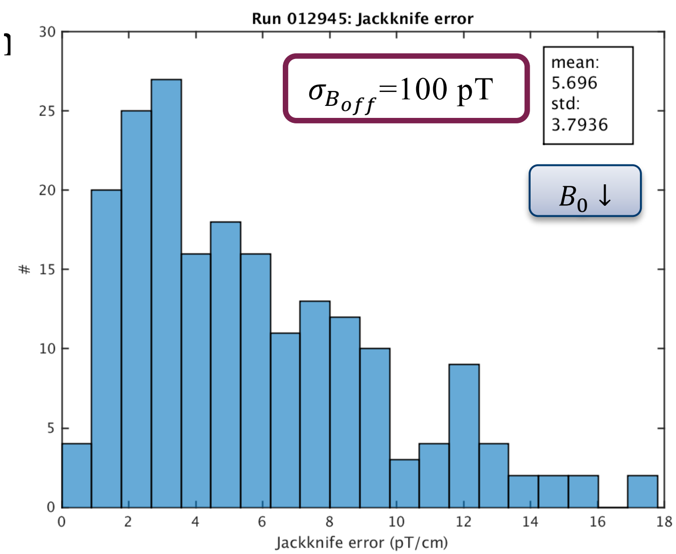
- Create 200 random sets of test fields from field-map gradients, ∀ 11 CsM

$$\overrightarrow{B_{test}}(\boldsymbol{r}) = \sum_{l=0}^{6}\left[G_{l,m}\,\vec{\pi}(\boldsymbol{r})\right] + \delta_{B_{off}}$$

↑

Gaussian distributed offset with various $\sigma_{B_{off}}$(50/100 pT)





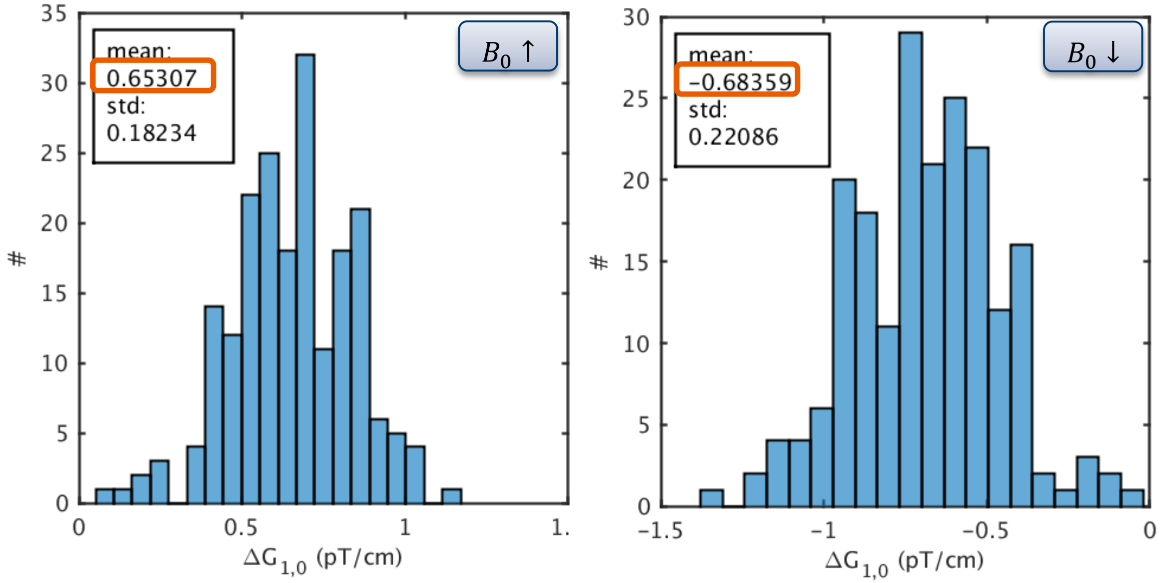
To obtain Jackknife error σ = 8 pT/cm, error for offsets should be $\sigma_{B_{off}}$=100 pT.

Simulated results (2)

- Generated test field: $\overrightarrow{B_{test}}(\boldsymbol{r}) = \sum_{l=0}^{6}\left[\left(G_{l,m} + \delta_{G_{l,m}}\right)\vec{\pi}(\boldsymbol{r})\right] + \delta_{B_{off}} \rightarrow G_{1,0}^{gen} = G_{1,0} + \delta_{G_{1,0}}$

  $\sigma_{B_{off}} = 118.5$ pT for 14 CsM

- With higher-order removal: $\pm\left|\overrightarrow{B_{test}}\right| - \sum_{l=3}^{6}\left[G_{l,m}\,\pi_z\right] \longrightarrow \sum_{l=0}^{2}\left[G_{l,m}\,\pi_z\right] \rightarrow G_{1,0}^{fit}$



Even with $\sigma_{B_{off}} = 118$ pT ,
$\Delta G_{1,0} \equiv G_{1,0}^{fit} - G_{1,0}^{gen} < 1$ pT/cm

Sensitivity improvement in magnetic-field gradient G_z is expected.